LOSSLESS CODING OF COLOR IMAGES
USING BLOCK-ADAPTIVE INTER-COLOR PREDICTION

Ichiro Matsuda, Tomokazu Kaneko, Akira Minezawa and Susumu Itoh

Department of Electrical Engineering, Science University of Tokyo
2641 Yamazaki Noda-shi, Chiba 278-8510, JAPAN
E-mail : matsuda@ee.noda.tus.ac.jp

ABSTRACT

This paper proposes a novel lossless coding scheme for color still images. The scheme employs a block-adaptive inter-color prediction technique to remove both spatial and spectral redundancy in RGB color signals. The resulting prediction errors are encoded using a context-adaptive arithmetic coding method. Several coding parameters which must be encoded as side information are iteratively optimized for each color signal. Experimental results show that the inter-color prediction technique provides better coding performance than a simple combination of reversible color transformation and intra-color prediction techniques.

***Index Terms*—** Color image coding, lossless coding, inter-color prediction, block-adaptive prediction, arithmetic code

1. INTRODUCTION

Color images, typically composed of R, G and B signals, have considerable correlations between each signal. Therefore exploiting such correlations is essential for efficient coding of color images. Color transformation is a simple way of decorrelating color signals, and often used as a preprocessing tool for color image coding. In the case of lossless coding, color transformation must also be lossless and lifting-based reversible color transformation techniques have been proposed [1, 2]. To enhance this approach, we investigated an adaptive color transformation method which changes lifting coefficients on a block-by-block basis [3]. However, when the method is combined with predictive coding, once decoded signals in different color spaces must be repeatedly transformed into another color space as reference signals for the succeeding prediction. This causes degradation of decoding speed as the prediction order becomes large. Furthermore, a straightforward combination of the color transformation and independent coding of the transformed color signals cannot yield the best result because color images have not only the intensity level correlations but also waveform or texture similarity between each signal [4].

In this paper, an efficient lossless coding scheme for color images is presented. The scheme directly encodes the original R, G and B signals using a block-adaptive inter-color prediction technique. Since the inter-color prediction cannot be applied to the first encoded signal (i.e. the G signal in this paper), its coding performance would be rather limited. However, when the remaining signals (the R and B signals) are being encoded, we can make use of information in the already encoded color signals by means of the prediction. Moreover, the inter-color prediction is carried out by computing a linear combination of many samples of different color signals in an adaptive way. It means that, at least for the last encoded signal, the adaptive inter-color prediction technique provides more flexibility in decorrelating color signals than the adaptive color transformation method [3] where the transformed signal is defined as a linear combination of up to three samples.

2. BLOCK-ADAPTIVE INTER-COLOR PREDICTION

In this paper, it is assumed that color images are composed of R, G and B signals each of which has 8-bit depth, and these signals are encoded one-by-one in the order of G→R→B. When the G signal is encoded, the block-adaptive prediction technique which we formerly developed for monochrome images [5] is applied in raster scan order. On the other hand, for the remaining R and B signals, the technique is extended to use already encoded color signals as shown

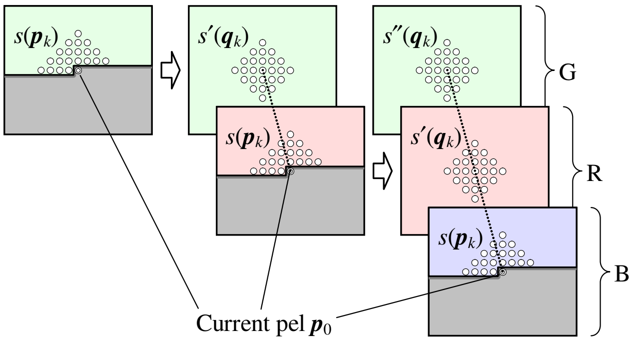

Fig. 1. Inter-color prediction.

in Fig. 1, where small circles indicate reference pels used for the prediction. Furthermore, all the color signals are partitioned into variable-size square blocks based on quadtree decomposition, and each block is classified into one of several classes. The class has an individual predictor which is optimized for its own class. In general form, a predicted value at a pel $\boldsymbol{p}_0$ in a block which belongs to the m-th class ($m = 1, 2, 3, \ldots, M$) can be expressed as:

$$\begin{aligned}\hat{s}(\boldsymbol{p}_0) &= \sum_{k=1}^{K} a_m(k) \cdot s(\boldsymbol{p}_k) \\ &\quad + \sum_{k=0}^{K'-1} a_m(k+K+1) \cdot s'(\boldsymbol{q}_k) \\ &\quad + \sum_{k=0}^{K''-1} a_m(k+K+K'+1) \cdot s''(\boldsymbol{q}_k), \qquad (1)\end{aligned}$$

where $a_m(k)$s ($k = 1, 2, 3, \ldots, K{+}K'{+}K''$) are prediction coefficients of the m-th predictor and $s(\boldsymbol{p_k})$ represents a value of the signal which is currently being encoded, while $s'(\boldsymbol{q}_k)$ and $s''(\boldsymbol{q}_k)$ are those of already encoded signals. The reference pels $\boldsymbol{p}_k$ ($k = 1, 2, 3, \ldots$) and $\boldsymbol{q}_k$ ($k = 0, 1, 2, \ldots$) are arranged in increasing order of city-block distance from the current pel $\boldsymbol{p}_0$ ($= \boldsymbol{q}_0$), but the positions of the former are limited in the causal half plane. During the G signal and the R signal are being encoded, the last two terms and the last term in the right hand side of Eq.(1) are omitted, respectively.

3. CODING OF PREDICTION ERRORS

After the inter-color prediction, context modeling for adaptive arithmetic coding of a prediction error $e = s(\boldsymbol{p}_0) - \hat{s}(\boldsymbol{p}_0)$ is performed. The context modeling is based on non-linear quantization of a context function which is defined as the weighted sum of absolute prediction errors in causal neighborhood [5]. Each quantization level of the function corresponds to one of sixteen contexts ($n = 1, 2, \ldots, 16$) and thresholds $\{Th_m(1),\ Th_m(2), \ldots, Th_m(15)\}$ used in this quantization are optimized for each class (m) as described later. We assume that, in consequence of this context modeling, a conditional probability density function (PDF) of the prediction error e observed in each context can be modeled by the generalized Gaussian function [6]:

$$\begin{aligned}P(e\,|\,n) &= \frac{c_n \cdot \eta(c_n, \sigma_n)}{2\,\Gamma(1/c_n)} \cdot \exp\Big\{ - \big|\, \eta(c_n, \sigma_n) \cdot e \,\big|^{c_n} \Big\}, \\ \eta(c_n, \sigma_n) &= \frac{1}{\sigma_n} \sqrt{\frac{\Gamma(3/c_n)}{\Gamma(1/c_n)}}, \qquad (2)\end{aligned}$$

where $\Gamma(\cdot)$ is the gamma function, σ_n is a standard deviation of the prediction errors and c_n is a shape parameter which controls sharpness of the PDF. Since 8-bit color signals contain integer values from 0 to 255, possible values of the prediction error e for a given value of $\hat{s}(\boldsymbol{p}_0)$ are also limited to the following 256 values:

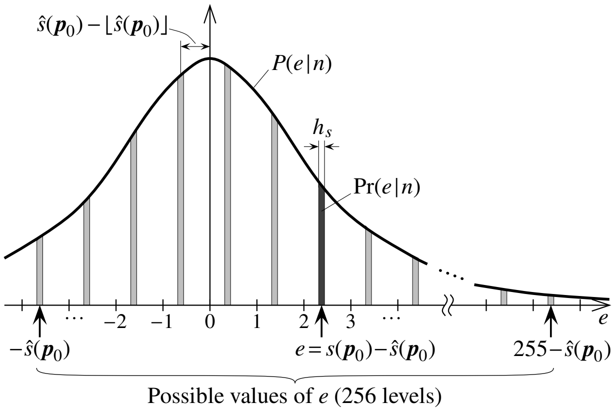

Fig. 2. Probability modeling for the prediction error e.

$$e \in \{ s - \hat{s}(\boldsymbol{p}_0) \mid s = 0, 1, 2, \ldots, 255 \}\,. \qquad (3)$$

Therefore, a conditional probability of occurrence for each possible value of e, when both the context n and the predicted value $\hat{s}(\boldsymbol{p}_0)$ are known, is derived from the above PDF.

$$\Pr(e \,|\, \hat{s}(\boldsymbol{p}_0), n) = \frac{\Pr(e \,|\, n)}{\sum_{s=0}^{255} \Pr(s - \hat{s}(\boldsymbol{p}_0) \,|\, n)}, \qquad (4)$$

$$\Pr(e \,|\, n) = \int_{-h_s/2}^{h_s/2} P(e + \varepsilon \,|\, n)\, \mathrm{d}\varepsilon. \qquad (5)$$

As a matter of fact, the predicted value $\hat{s}(\boldsymbol{p}_0)$ is explicitly rounded to the nearest multiple of $h_s = 1/8$ to avoid accumulation of unexpected rounding errors. Hence the value of h_s is used as an interval for integration of the PDF in Eq.(5). Adaptive arithmetic coding of the actual value of e is carried out according to the conditional probabilities calculated by using Eqs.(4) and (5). Note that the numerator of Eq.(4) corresponds to the area shown in dark gray and the denominator is the sum of the shaded areas in Fig. 2. Practically, by storing all of the probabilities in a look-up table at a sampling rate of $1/h_s$, we can considerably reduce computation required for the adaptive arithmetic coding.

4. OPTIMIZATION OF CODING PARAMETERS

In the proposed coding scheme, parameters listed below are optimized for each color signal and transmitted to the decoder as side information.

- Quadtree for variable-size block partitioning.
- Class label m for each variable-size block.
- Prediction coefficients $a_m(k)$s for each class.
- Thresholds $\{Th_m(n)\}$ for each class.
- Shape parameter c_n for each context.

Optimization of these coding parameters is done by iteratively minimizing the following cost function:

$$J = -\sum_{\boldsymbol{p}_0} \log_2 \Pr(e \mid \hat{s}(\boldsymbol{p}_0), n) + B_{side}. \qquad (6)$$

The first term of the cost function represents the number of bits required for the adaptive arithmetic coding of the prediction errors. The second term (B_{side}) is the amount of side information on the above coding parameters. Concrete procedures for minimizing the cost function J are as follows.

(1) Blocks composed of 8×8 pels are classified into M classes according to variance of the color signal within the respective blocks. Then initial predictor is designed for each class [7].

(2) Prediction coefficients of each predictor are iteratively optimized. The detailed procedure will be shown in the next section.

(3) A set of thresholds $\{Th_m(1), Th_m(2), \ldots, Th_m(15)\}$ used for the context quantization is optimized for each class by using the dynamic programming technique.

(4) The optimum value of the shape parameter c_n is selected from sixteen values $(0.2, 0.4, 0.6, \ldots, 3.2)$ in each context.

(5) Every square block of 32×32 pels is recursively divided according to a four-level quadtree while choosing the best predictors, and the optimum combination of block sizes and class labels (m) is determined [5].

(6) Procedures (2), (3), (4) and (5) are iteratively carried out for each color signal until all of the coding parameters converge.

5. OPTIMIZATION OF PREDICTORS WITH VARIABLE PREDICTION ORDER

In the previous work, the parameter K which defines prediction order is fixed during the optimization procedures and its recommended value is experimentally given as a function of image size [5, 6]. However, in the case of inter-color prediction, there are up to three parameters regarding the prediction order (K, K', K'') and their appropriate values would be different for each color signal. This makes difficult to set these parameters manually in advance. Therefore, we introduce a modified optimization procedure which enables automatic setting of the prediction order, or disposition of reference pels in the strict sense, for each predictor.

At first, we design the initial predictors under relatively small setting of the above parameters, for example $K = 12$ and $K' = K'' = 25$ are used for B signal. Next, their values are increased to $K = 110$ and $K' = K'' = 221$ respectively, and newly added prediction coefficients are set to zero. Then, a prediction coefficient $a_m(i)$ is randomly selected from among non-zero ones, and a certain value of $\pm\Delta a$ is temporarily added to the coefficient $a_m(i)$. At the same time, the value with opposite sign ($\mp\Delta a$) is added to other coefficients $a_m(j)$s ($j = 1, 2, 3, \ldots, K + K' + K''$; $j \neq i$) in turn. Moreover, when the value of $a_m(j)$ is zero, we test the extra case of exchanging the values of $a_m(i)$ and $a_m(j)$. Among these numerous trials, the best one which minimizes the cost function J is actually accepted. This process of coefficient refinement is repeated several times for every predictor as the procedure (2) of the section 4. To obtain better convergence of the prediction coefficients, the value of Δa is halved step-by-step from $1/64$ to $1/256$ in the optimization procedures. The final value of $\Delta a = 1/256$ is also used as a quantization step-size for coding of the optimized prediction coefficients. To be specific, positions of non-zero coefficients are first designated by binary information as shown in Fig. 3, and their quantized values are then encoded using a multi-symbol arithmetic coder.

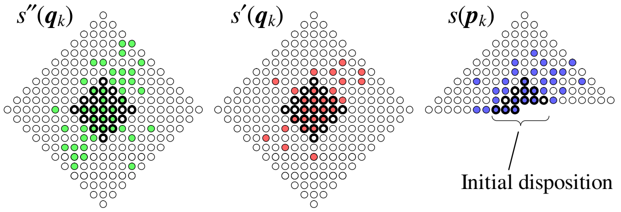

Fig. 3. Example of disposition of reference pels (B signal).

6. EXPERIMENTAL RESULTS

To evaluate coding performance of the proposed scheme, we have conducted several experiments using RGB 24 bit color images composed of 512×512 pels. Table 1 lists coding rates of our lossless coding schemes where the number of predictor is set to $M = 20$ for all color signals. 'Inter-color' is the proposed scheme using the variable block-size adaptive inter-color prediction, while 'Intra-color' means independent coding of three color signals (i.e. K' and K'' are always set to zero). Additionally, 'with CT' indicates

Table 1. Comparison of coding rates (bits/pel).

Image	Inter-color (proposed)	Intra-color with CT	Intra-color without CT
Airplane	**10.121**	10.531	11.059
Lena	**11.872**	12.588	12.526
Mandrill	**16.041**	17.070	17.230
Milkdrop	**9.267**	11.196	9.758
Peppers	**8.414**	9.304	10.508
Sailboat	**13.678**	14.359	14.337
Average	***11.566***	*12.508*	*12.570*

Table 2. Comparison with state-of-the-art schemes (bits/pel).

Image	Proposed	BMF	WinRK	CALIC	JPEG-LS	JPEG-2K
Airplane	**10.121**	10.496	10.594	11.025	11.275	11.652
Lena	**11.872**	12.277	12.730	13.218	13.532	13.585
Mandrill	**16.041**	16.781	17.227	17.819	18.125	18.080
Milkdrop	**9.267**	9.792	9.683	11.990	12.033	11.905
Peppers	**8.414**	9.190	9.331	10.429	10.432	10.231
Sailboat	**13.678**	14.469	14.899	15.454	15.872	16.045
Average	***11.566***	*12.168*	*12.411*	*13.322*	*13.545*	*13.583*

that the reversible color transformation technique described in the JPEG-LS part 2 specification [8] is applied before the independent coding. Since the color transformation technique uses modulo arithmetic to preserve required bit depth through the transformation, it rarely produces excessive discontinuity in the transformed color signals. This is the reason why coding performance of some images degraded by using the color transformation technique though the average coding rate is improved. On the other hand, the proposed scheme always yields the best result among the three schemes and the average reduction of coding rates obtained by the inter-color prediction reaches about 9 %.

Table 2 also lists the coding rates of the proposed scheme together with those of other state-of-the-art lossless coding schemes: BMF (version 2.0) [9], WinRK (version 2.1.6, PWCM mode) [10], CALIC [11], JPEG-LS [12] and JPEG 2000 [13]. In this experiment, CALIC and JPEG-LS use the same reversible color transformation technique [8]. We can confirm that the proposed scheme attains the best coding performance for all tested images and its coding rates are 3–8 % lower than those of the BMF scheme which shows the second best results for most images.

7. CONCLUSIONS

We have proposed an efficient lossless coding scheme for color images. The scheme employs a variable block-size adaptive inter-color prediction technique to remove both spatial and spectral redundancy in the original RGB color signals. In order to design a set of predictors suitable for each color signal, a modified procedure for optimizing the predictors with variable prediction order is introduced. Experimental results show that the proposed scheme has a distinct advantage over the scheme based on a simple combination of reversible color transformation and intra-color prediction, and as a result, outperforms other state-of-the-art lossless coding schemes in terms of coding efficiency. Though computational complexity of encoding process is relatively high due to the iterative optimization procedures, decoding speed of the proposed scheme can be reasonably fast. When image size is 512×512 pels, for example, our prototype codec takes several tens of minutes in encoding and at most 0.5 seconds in decoding on a computer with the 3.6 GHz Xeon processor. Fast implementation of the encoding process will be a part of our future work.

8. REFERENCES

[1] S. Fukuma, M. Iwahashi and N. Kambayashi, “Lossless Color Coordinate Transformer for Lossless Color Image Coding,” Proc. of IEEE Asia-Pacific Conf. on Circuits and Systems (APCCAS’98), pp. 595–598, Nov. 1998.

[2] P. Hao and Q. shi, “Comparative Study of Color Transforms for Image Coding and Derivation of Integer Reversible Color Transform,” Proc. of 15th Intl. Conf. on Pattern Recognition (ICPR’00), Vol. 3, pp. 224-227, Sep. 2000.

[3] I. Matsuda, H. Mori and S. Itoh, “Lossless Coding of Color Images Using Adaptive Lossless Color Transformation and Minimum-Rate Predictors,” Proc. of the International Picture Coding Symposium (PCS 2001), pp. 199-202, Apr. 2001.

[4] S. Benierbah and M. Khamadja, “Compression of Colour Images by Inter-Band Compensated Prediction,” IEE Proc. Vision, Image and Signal Processing, Vol. 153, No. 2, pp. 237–243, Apr. 2006.

[5] I. Matsuda, N. Ozaki, Y. Umezu and S. Itoh, “Lossless Coding Using Variable Block-Size Adaptive Prediction Optimized for Each Image,” Proc. of 13th European Signal Processing Conf. (EUSIPCO-2005), WedAmPO3, Sep. 2005.

[6] I. Matsuda, N. Shirai and S. Itoh, “Lossless Coding Using Predictors and Arithmetic Code Optimized for Each Image,” Proc. 8th Int. Workshop VLBV03, Lecture Notes in Computer Science Vol. 2849, pp. 199–207, Sep. 2003.

[7] I. Matsuda, H. Mori and S. Itoh, “Lossless Coding of Still Images Using Minimum-Rate Predictors,” Proc. of 2000 IEEE Intl. Conf. on Image Processing (ICIP-2000), Vol. I, pp. 132–135, Sep. 2000.

[8] ISO/IEC JTC 1/SC 29/WG 1 N1687, “JPEG-LS part-2 (14495-2),” FCD Ver. 1.0, Apr. 2000.

[9] http://compression.ru/ds/

[10] http://www.msoftware.co.nz/

[11] X. Wu and N. Memon, “Context-Based, Adaptive, Lossless Image Coding,” IEEE Trans. on Communications, Vol. 45, No. 5, pp. 437–444, Apr. 1997.

[12] ISO/IEC, ISO/IEC 14495-1:1999, “Information Technology – Lossless and Near-lossless Compression of Continuous-Tone Still Images: Baseline,” Dec. 1999.

[13] ISO/IEC JTC 1/SC 29/WG 1, ISO/IEC FCD 15444-1, “Information Technology – JPEG 2000 Image Coding System,” Mar. 2000.